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Channel cracking in inelastic film/substrate systems

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ABSTRACT

Studies on channel cracking are generally limited to elastic films on elastic or inelastic substrates. There are important applications were the cracking process involves extensive plasticity in both the film and substrate, however. In this work steady-state channel cracking in inelastic thin-film bilayers undergoing large-scale yielding from thermal or mechanical loading is studied with the aid of a plane-strain FEA. The plasticity of the film and substrate, represented by a Ramberg–Osgood constitutive law, each increases the energy release rate (ERR) relative to the linearly-elastic case. This effect is more pronounced under mechanical loading where the entire bilayer undergoes large-scale yielding. To help assess the analytic approach some fragmentation tests are performed using a well-bonding epoxy/aluminum system. The analysis reproduced well the observed dependence of crack initiation strain on film thickness.

Ultra-thin films may be well represented by an elastic-perfectly plastic response. For such films on a flexible support the ERR remains fixed as the applied strain exceeds the yield strain of the film. Accordingly, a critical coating thickness exists below which no channel cracking is possible. The explicit relations and graphical data presented may be used for optimal design of such structures against premature failure as well as for determining fracture energy of ductile thin films.

1. Introduction

Thin coatings are prone to crack in a channel mode under tension. There are important applications where the process of fracture is accompanied by extensive plastic deformation in the coating, the substrate, or both. Examples include wear-resistant hard coatings on ductile substrates, polymeric paints in the automotive industry (Nichols et al., 1999; Nichols, 2002) and ultra thin metal interconnectors on a flexible support (Macionczyk and Bruckner, 1999; Alaca et al., 2002; Niu et al., 2007; Chen and Gan, 2007; Gruber et al., 2009; Lu et al., 2010). While channel cracking in linearly-elastic systems has been studied extensively starting with the notable works of Gille (1985), Nakamura and Kamath (1992) and Beuth (1992), similar studies on inelastic systems are generally limited to linearly-elastic films on nonlinear substrates undergoing localized yielding, as is the case for thermal type loading (Beuth and Klingbeil, 1996; Ambrico and Begley, 2002). Beyond the usual concerns for structural integrity, channel cracking offers a viable means for determining fracture energy in elastic thin films (Hsueh and Yanaka, 2003; Andersons et al., 2008; Miller et al., 2009; Pinyol et al., 2009), generally with the aid of the steady-state analysis of Beuth (1992). Often this approach is also adopted for ductile films (Macionczyk and Bruckner, 1999; Alaca et al., 2002; Niu et al., 2007; Chen and Gan, 2007), although its validity is yet to be assessed.

The analysis of channel cracking in bilayers undergoing large-scale yielding poses a formidable challenge. The fracture process may involve crack penetration into the substrate (Gille, 1985; Wellner et al., 2004), delamination between film and substrate and other complex fracture modes not strictly consistent with classical channel cracking. As an example we note the fragmentation tests on Cu/polyimide systems by Lu et al. (2010), who observed a transition from off-axis inter-granular to trans-granular fracture accompanied by local debonding as the film thickness increased from 200 nm. Such results allude to the intricate role played by grain size and grain texture, and in turn film thickness, on the fracture behavior of sputtered ductile films. In addition, as for any ductile material there is the issue of a proper interpretation of fracture energy and the role of film thickness on this quantity.

In this work we consider channel cracking in inelastic film/substrate systems from thermal as well as mechanical loading, where the entire bilayer may undergo large-scale yielding at onset of fracture. Our analysis is limited to the steady-state energy release rate (ERR), here determined with the aid of a plane-strain Finite Element Analysis (FEA) incorporating large deformation and material nonlinearity. To assess the analytic approach, fragmentation tests are carried out on a model system geared toward alleviating some of the difficulties noted above. The specimen consists of a thin epoxy-resin coated onto a dog-bone shaped ductile aluminum alloy (Fig. 1a). When sufficiently thin this resin undergoes extensive plastic deformation before it cracks. This, together with its excellent bonding capability and isotropic mechanical properties

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